Flow Measurement at Dr. Gabriel Terra Power Station using Current Meter Method

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Abstract

This paper presents a technical review and discussion of experiences gained during recent flow measurement tests at Dr. Gabriel Terra Power Station, using the current meter method. These test were undertaken in order to determine the absolute efficiency of the turbines after their renovation. The article illustrates how greater accuracy of flow measurement was made possible by increasing the number of current meters and frame arms used.

Background

The Dr. Gabriel Terra Power Station is located on the Rio Negro, in the centre of Uruguay, and originally entered into full service in 1948, with the four Kaplan generating sets providing a total rated power output of 128 MW. Recently these units were fully refurbished, including replacement of each of the original 6-bladed Kaplan runners with new 5-bladed runners. This refurbishment has resulted in a maximum uprate in scheme power output of some 22%, and an average increase in turbine efficiency of 4%. A section of the turbines and intakes is shown in Figure 1.

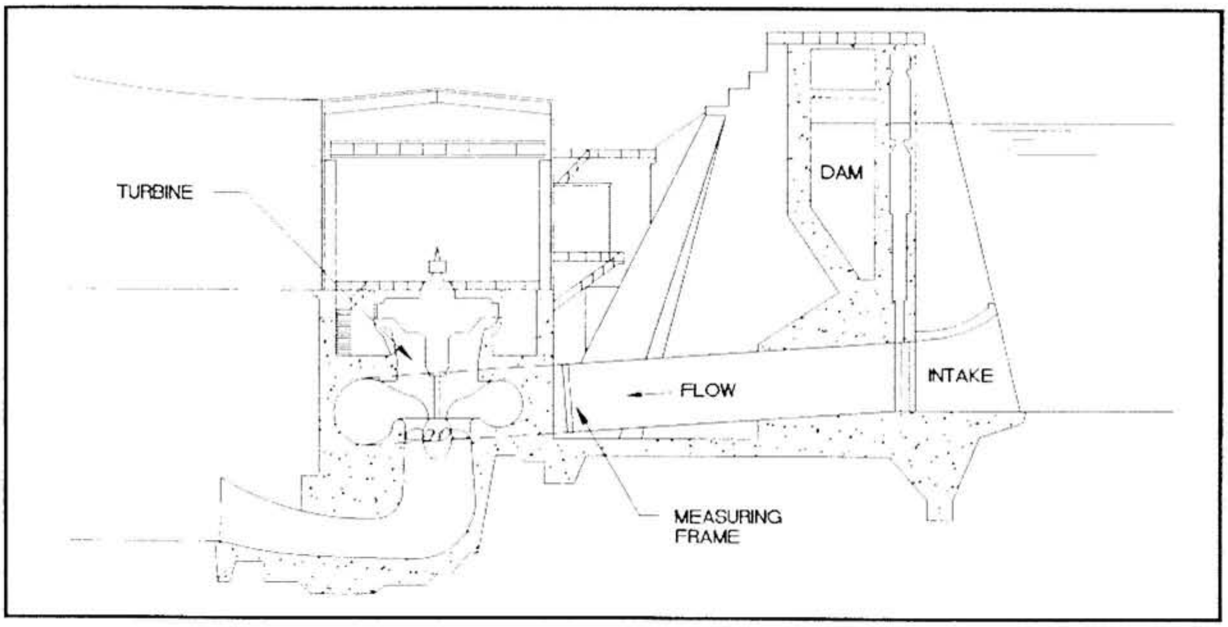


Figure 1 Layout of Dr.Gabriel Terra Hydro-Electric Scheme

This refurbishment project was managed by Administración Nacional de Usinas y Trasmisiones Eléctricas (UTE) of Uruguay, with specialist advice and site supervision services being provided by Merz and McLellan Consulting Engineers of the United Kingdom. Merz and McLellan have been involved with site testing of water turbines since 1937 [1], and were also instrumental in the early development of the British Standards on this topic [2], since then being involved in over a dozen site tests worldwide.

Layout of Intake Waterways

Each of the Kaplan turbines on this scheme receives flow through individual steel penstocks of 7m diameter and 39m length. Both the intakes and penstocks are of short length as defined by IEC41, and some degree of non-uniformity of the flowfield at spiral inlet has been suspected.

The shape of velocity profile at spiral entrance was determined for a number of the turbines prior to the renovation, using a system of 25 current meters mounted on a 4-arm frame. Comparative measurements were performed in the same section of penstock, using the same layout of current meters, and near-identical flow characteristics were obtained from one unit to another.

However, these results clearly indicated slight characteristic skewness of the velocity profile towards the lower half of the penstock, with a small degree of localised flow instability being noted from some of the current meter readings. Although these velocity profiles were typical for large pipe flows, a far more detailed velocity pattern was seen to be required to gain sufficiently accurate values of total flow, using the numerical integration method, and a refinement to the basic measuring layout was required.

The recommendations of the ISO3354 standard [3] can be applied with relative ease in conventional cases of scheme layout, ie, where intake flows are essentially parallel and symmetrical with respect to the of penstock axis, without exhibiting significant secondary flows nor excessive turbulence. Good measuring conditions can typically be attained when the length of straight pipe before and after the measuring section is of a minimum of 20 and 5 diameters respectively. For these conditions, and for a pipe diameter of 7m, IEC41 [4] recommends using 33 current meters mounted on a structure of 4 arms.

However in the case of Dr Gabriel Terra, the total length of straight pipe is 39m, equivalent to 5.6 diameters, a value much lower than recommended for the conventional layout. Thus it was clear that the number of current meters had to be increased, and therefore additional radial arms were necessary.

The literature also highlights elsewhere how the use of additional arms can help increase the measuring accuracy significantly. For example, at the velocity exploration tests reported at Brisay [5], the calculated flow variation compared between 4 and 8 arms was found to differ by some 0.2%. At Laforge-1, a similar "short" arrangement as the present one was used, with flow measuring uncertainties of 1-2% being validated through use of other flow measuring methods [6]. This data compares well with our own experience, and it was apparent in this case that more grid refinement was necessary.

Penstocks

The intake penstocks at Dr Gabriel Terra are constructed from segments of riveted overlapping plate. The localised turbulence effects of these steps was believed to cause further distortion of the velocity profile near the walls, and use of small close-fitting current meters would be required to capture this behaviour.

As mentioned previously, the intake flowfield is not believed to be fully uniform or developed by the time it reaches the turbine spiral casing, due to the short length of penstock. Further modifications to the flow profile were also believed to be caused by larger-scale geometric effects. Although the concrete intakes curve quite smoothly, the frontal section of each penstock changes from square to circular section over a relatively short transition. As such, longer-term secondary flows were suspected within the penstock, possibly resulting in a relatively complex flowfield pattern at the position of measuring section.

Overall such factors make it difficult to measure the flow precisely using the conventional velocity-area method. In order to more accurately capture the shape of velocity profile at spiral entry, a specially customised measuring layout was developed. This consisted of 60 propeller-type current meters arranged concentrically on a specially tailored 8-arm frame. After a period of detailed planning and installation, the efficiency tests were conducted jointly by UTE and the turbine refurbishment contractor, GEC Alsthom Neyrpic.

New 8-Arm Measuring Frame

The new frame was constructed in the same measuring plane as the original frame to enable index-type comparisons to be made between the turbines. The frame was modified by joining 4 extra radial arms to the original 4-arm frame, with each of the 8 arms mounted at 45° from each other, as shown in Figure 2. The entire assembly was bolted to the penstock walls, and intermediary supporting ribs were welded in situ, being arranged in a "spider's web" fashion. The arrangement was unusual for an 8-arm current meter layout in that it was of the non-straddled type, as opposed to the more usual vertical centreline-straddled layout. An overall blockage factor of 3.5% was calculated for the frame.

Three different makes of current meter were used, OTT, Dumas Neyrpic and SEBA, with an assortment of different propeller diameters (∅50mm, ∅80mm, ∅100mm, and ∅120mm). On each of the four original radial arms, 7 current meters were affixed (6x∅120, and 1x∅50), similarly on each of the 4 supplemental radial arms, 8 current meters were affixed (1x∅80mm, 6x∅100mm and 1x∅50mm), making 60 total. Each of the 8 peripheral current meters was chosen of ∅50mm size. All current meters were mounted concentrically within the penstock in accordance with ISO3354 specification, and in this case arranged so that all the different propeller sizes were symmetrically balanced in the orthogonal planes.

In the frame centre, a large bracket-type joint was required to provide mechanical strength to the entire frame, as large hydraulic forces were expected during normal turbine operation. The resulting obstructive effect was also believed to alter the velocity profile slightly in the central core-zone of flow. To investigate this effect, a single current meter was installed in the frame centre for comparison. However for the flow integration calculation, inputs for the central velocity at r_0 were obtained by averaging the velocities of the four current meters on the innermost ring at $r_{0.5}$.

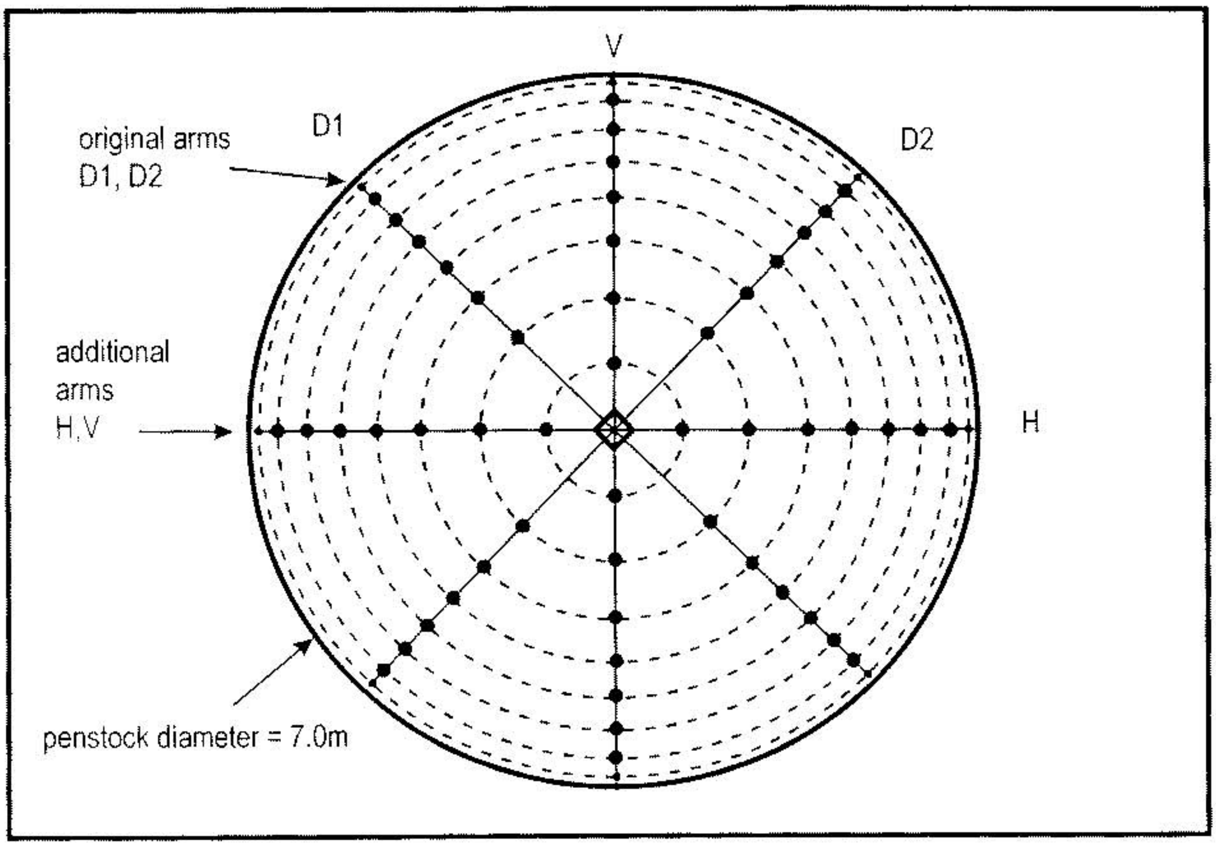


Fig. 2. Layout of measuring frame

It was also deemed important to use small close-fitting current meters adjacent to the penstock walls in order to adequately penetrate the "boundary" layer. However this distance was effectively limited to the recommendations of ISO3354 in order to avoid interference effects and instability problems which have been experienced elsewhere. Also the use of large current meters was not favoured in the periphery, as this can lead to an underestimation of the velocity (by as much as 0.5% relative to smallest propellers). In addition, excessive close-fitting was believed to lead to further possibility of underestimation of velocity measurement, due to the averaging-error effect of the propeller swept path as compared to the extrapolated velocity profile based on log-law. A proximity correction could have been appropriated based on specialised laboratory calibrations, but this was not necessary for these tests.

Calibration

The 60 current meters used were calibrated in 2 separate batches, in independent laboratories in Montevideo (Uruguay), and Ittigen (Switzerland). Each set of current meters was calibrated in tow-tanks, using the same supporting frame profile, and all calibrations were performed according to ISO3345 standard. Calibration characteristics such as velocity/count relationships for individual current meters were entered directly into the computer data acquisitioning programme prior to testing.

Installation

The installation of all the equipment at site was undertaken in around 10 days, with all the frames and current meters being manhandled through two small access ports in the penstock lining. Current meter cabling was wired internally in the frames themselves, and collectively routed through a number of pressure-tight glands in the penstock walls. The penstock diameter was checked in a number of positions using a portable laser instrument.

Overall the installation phase had been well-orchestrated, and practical difficulties were largely minimised by good planning and co-ordination between the test parties, well in advance of the tests themselves. As such the test programme at site was not subject to any significant delays.

Efficiency Test and Practical Difficulties

The efficiency test was undertaken in 1997, over a duration of approximately 3 weeks. After initially watering-up the turbine, system connectivity tests and a number of trial runs were performed. A number of current meters were noted to exhibit abnormal behaviour, falsely indicating significantly higher velocities than recorded on adjacent current meters, particularly at higher flowrates. After analysing the defective signals on oscilloscope, it was apparent that the frame support was vibrating and interfering with the switching mechanism inside a number of current meters.

The turbine was subsequently dewatered and inspected. Some of the current meters were found to be slightly mis-orientated with weakened or loosened screw clamps. Some of the reinforcing rods had also been torn off and ingested in the turbine, although some of these pieces were later found on the spiral floor. A number of larger support bars were later re-welded back to the frame to strengthen up the assembly.

After the machine was watered up and restarted, all current meters showed normal behaviour. Throughout the remaining tests, the behaviour of all the current meters was within pre-set acceptance limits, and only one failure was recorded. This defective current meter was located at the bottom of the penstock, the cause of failure believed to be due to signalling rather than mechanical fault.

Two separate sets of data acquisition system (DAI) were used in parallel, one serving 28 current meters and the other serving 32 current meters. In order to verify the confidence of the equipment, and coherence of data recording, sample measurements were made by interchanging given current meters with each DAI, and the results were found to be in agreement. The final values of velocity outputs obtained were averaged for each concentric radius.

With regard to the close-wall placement of peripheral current meters, no irregular behaviour was recorded that could be attributed solely to localised turbulence effects of the overlapping penstock plates and rivets. In addition no significant interference effects were detected.

Measuring Uncertainty

Evaluation of uncertainties within the flow measuring process was made by assessment of all the individual sources of error. A total measuring uncertainty value of ±1.45% was finally estimated for the tests. Of this figure, a portion of some ±1.0% uncertainty was attributed to fluctuations in local velocity measurements, a value which compares well with our experience. In addition, the low current meter failure rate and accurate measurement of penstock section were factors which helped to minimise the measuring uncertainty.

Test Results

During testing, flow measurements were taken at some 90 different points of turbine operation, between flows of 75 m^3/s and 160 m^3/s. Each individual flow test point was of 600 seconds duration.

Because of the large headwater capacity, the gross head levels changed very little during the tests, and a net head of 26m was recorded for rated conditions. Values of the coefficient "m" obtained for the penstock were close to 9.

All the data acquisition was handled in full by PC, which greatly facilitated analysis and post-processing of results. From the test results outputs, the following characteristics were noted:

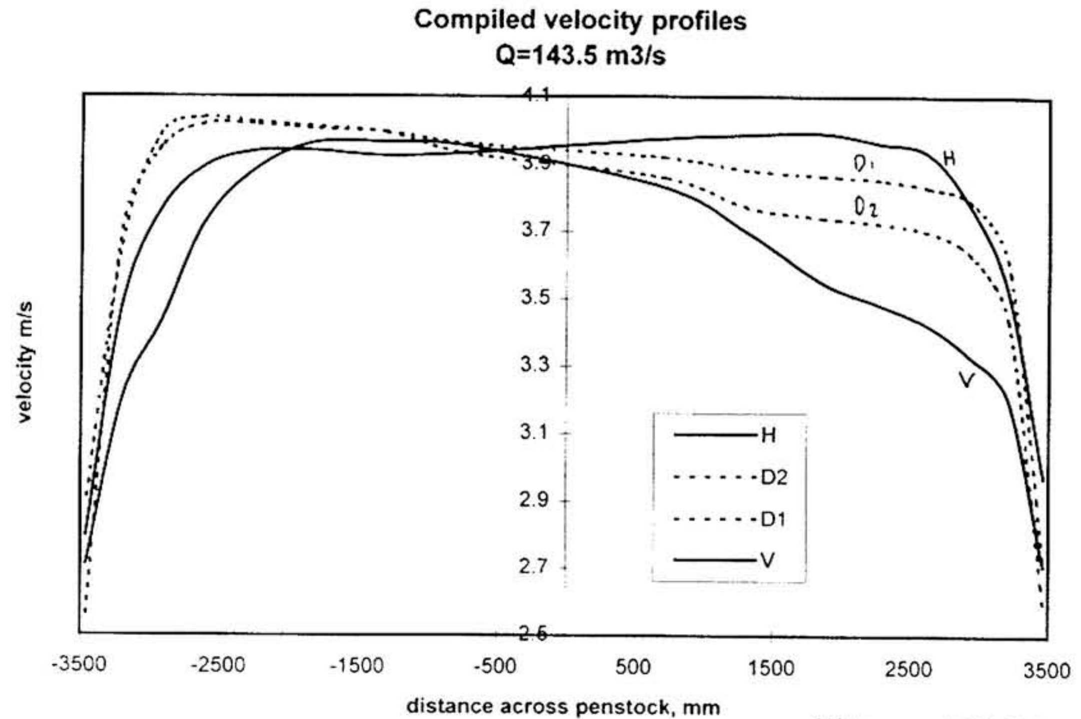
a) Flow profiles:

When analysed collectively, the velocity outputs provided a detailed insight of the three-dimensional flow profile. Although conventional large-pipe flow characteristics were clearly observed, some degree of flow asymmetry was also noted across the vertical (V) and diagonal (D_1, D_2) planes. Conversely, the horizontal plane (H) was remarkably symmetric. The velocity profiles in both orthogonal planes were also noted to differ significantly from those in the diagonal planes, as shown in figure 3a. Figure 3b shows a sketch of the interpolated flow contours obtained nearer maximum flowrate conditions.

Of particular interest was the detection of relatively lower bulk-velocity regions, in both the upper and very lower part of the penstock. Also a strong central core flow was apparent in the lower third of the penstock. However the results did not indicate any significant secondary flows or localised flow instabilities across the range of flowrates tested.

b) Central Blockage Effect:

To quantify the blockage effect caused by the central joint, and subsequent effect on velocity profile, a comparison was made between readings from the central current meter, and the corresponding average of the four on the innermost ring at $r_{0.5}$. In all the tests, a remarkably good correlation was observed, and as expected the central core velocity u_0 at r_0 was shown to be comparatively lower, the difference in velocity being of the order of 6.5%, this figure increasing slightly to 8% at the lower flowrates. This was equivalent to a difference in total flow calculated of 0.2%



H,V, source: GEC Alsthom Neyrpic.

Figure 3a. Compiled velocity profiles for Q=143.5m3/s.

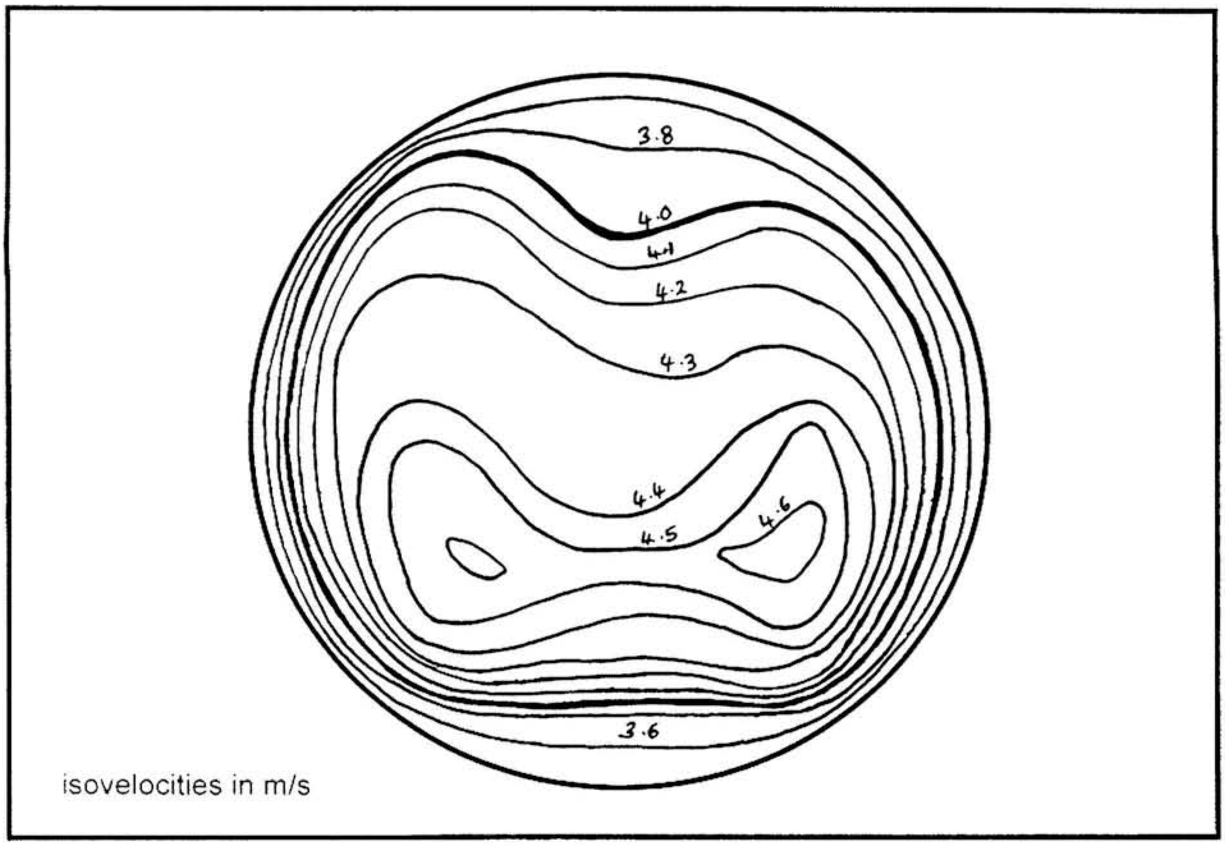


Figure 3b. Sketch of flow contours for Q=160.0m3/s.

c) Efficiency Results:
Final hydraulic efficiency values were derived from the flow values, and these showed characteristics which were close to expectations. In determining values of efficiency, additional errors in head and power measurement were also taken into account.

d) Repeatability:
Overall the repeatability of test points was good, being within some ±0.2%. Near-identical repeatability of velocity profiles was also shown for the same flow points at very similar heads, even though measured many hours apart. For the example shown in figure 4, the repeatability of diagonal velocity profiles is shown for two cases of Q=127.0 m^3/s and Q=127.9 m^3/s (corrected to Q=127.0 m^3/s), which were measured some 90 hours apart, under slightly different operating conditions.
In addition to good repeatability, all four velocity profiles were observed to change remarkably uniformly throughout the range of turbine operation, as the example in figure 5 shows, highlighting the absence or onset of any macro-hydraulic instability effects, even at large flowrates.

Conclusion

The refinement to the flow measuring layout had facilitated a significant increase in both the confidence of the data measured, and scope of data captured. The tests also demonstrated how good measuring conditions can still be obtained for schemes with short intakes, provided that certain guidelines are followed. However some hydraulic knowledge of the flow characteristics is required *a priori* in order to be able to fully optimise the measuring system for the given scheme layout, either by assessing previous site measurement data, or perhaps using numerical flow simulation methods.

The results in this case showed that, when only considering the original 4 radial arms, an effective increase in the number of current meters from 6 to 8 on each arm had very little influence on the flow calculation. Conversely, the use of 28 additional current meters on 4 supplemental arms created a significant modification in the final values of flow calculated. Overall, in determining a value of total flow based on only 32 current meters mounted on the original 4-arm frame, a flow value was obtained which was approximately 2% higher than that calculated using the total compliment of 60 current meters. Thus it can be assumed that the flow measurements for the original frame of 25 current meters (used prior to the renovation) were affected by an additional systematic error of the order of 1%.

In this case, it can be stated that further significant improvements in measuring uncertainty would not be likely if more than 8 arms or more than 60 current meters were fitted. However, further mechanical improvements to the measuring frame could be made in order to both decrease the blockage effect slightly, and also improve the frame arm profile in order to minimise flow-induced vibration. Great emphasis is also placed on good planning and co-ordination of the tests beforehand.

However the need is highlighted to refine the test standards (IEC41) further, in instances where 8 or more arms are necessary.

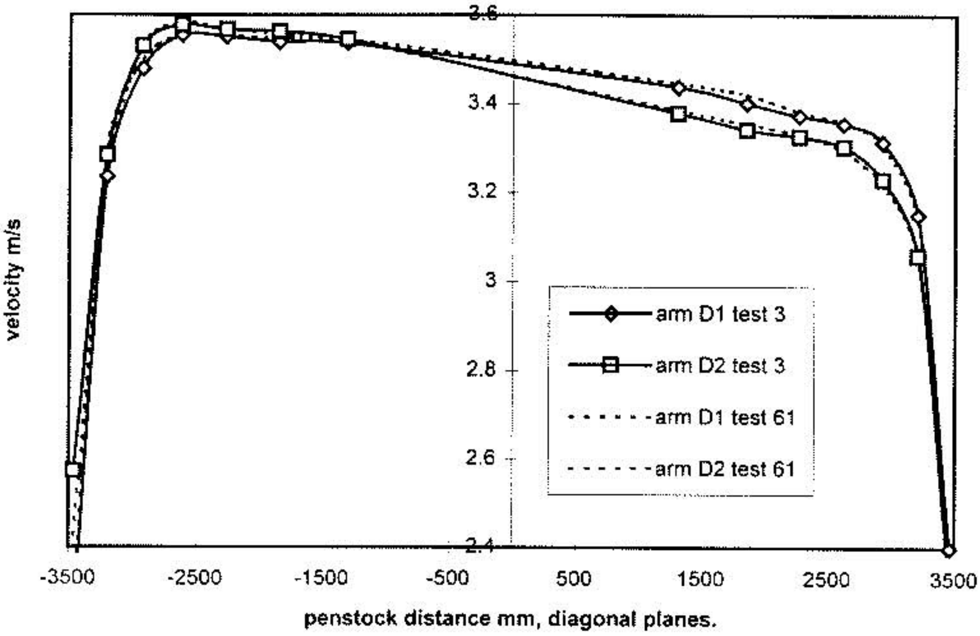


Fig.4. Repeatability of flow profiles D1 and D2 at Q=127.0 m3/s.

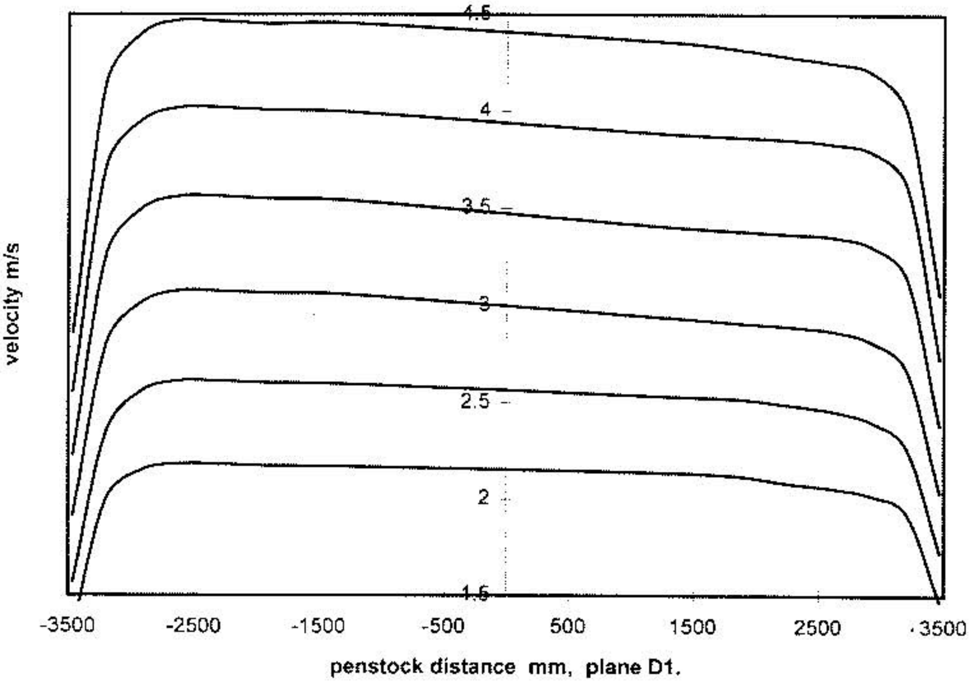


Fig.5. Flow profiles in diagonal plane D1, shown in increments of 10% between Q/Qmax= 95%-45%.

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